Use of STAP techniques to enhance the detection of slow targets in shipborne HFSWR

Marc LESTURGIE
Office National d'Etudes et Recherches Aérospatiales (ONERA)
Chemin de la Hunière et des Joncherettes, F-91761 Palaiseau
Email : marc.lesturgie@onera.fr, Tel. : +33-1-69936288, Fax : +33-1-69936269

Abstract - **This paper addresses the detection of low velocity target from a shipborne HFSWR (High Frequency Surface Waves Radar). In a shipborne configuration, as a consequence of the ship motion first order of Bragg lines is spread in the useful Doppler interval where detections of ship target are expected to appear. Space time techniques like STAP, usually studied for airborne radar purposes are candidate to reduce the effect of ship motion. Influence of pitch and roll components is also discussed. Simulations of STAP techniques are given, based on a conventional architecture of processing. Estimation of the clutter covariance matrix is studied with respect of the characteristics of the radar waveform. Interleaving between the classical HFSWR waveform and a wide band learning waveform is proposed to enable the covariance estimation.**

I. INTRODUCTION

Surface waves propagation is well known for its benefit to radar detection of target beyond the horizon. There are a lot of references and published papers on applications of HF surface waves radar (HFSWR) to oceanography (sea current measurement) , target detection and tracking. Most of the HFSWR systems are onshore radar and provide interesting detection performances against low altitude targets like missile, stealth aircraft or vessels. However, when the radar has to be mounted on a shipborne platform, additional problems have to be solved, such as HF antennas integration, E.M. compatibility and *motion compensation*. In a shipborne configuration the first order Bragg lines is spread, making the detection of ships more difficult than in a onshore configuration, because the Doppler frequency of these targets are expected to appear in the spreading clutter domain. This effect is as more problematic as velocities of the ship (hosting the radar) and the ship target present the same order of magnitude.

Shipborne HFSWR configuration is similar to airborne early warning configuration where low altitude target echoes are embedded in the ground spread clutter. To counter this effect, signal processing techniques like DPCA (display phase center antenna) and - more recently - STAP (Space Time Adaptive Processing) can be used to restore the performances. During the last ten years, the abundance of studies and works to optimise STAP architecture was coming from airborne radar domain, and purpose of this paper is study whether these algorithms can be adapted and finally implemented on a shipborne HFSWR to help the detection of slow targets.

Purpose of the first part of this paper is to remind the basement of physics of Bragg scattering. In a second part, simulations of Bragg clutter in a motion configuration are presented. The third part describes the possible architecture of a STAP processor with respect to the HFSWR specificity. Simulations are presented to assess the feasibility of STAP and the problem of clutter covariance matrix is discussed.

II. SEA CLUTTER IN HFSWR

Sea clutter consists of 1st order and second order of Bragg lines, within an interval of a few Hz. The 1st order, as received by an onshore radar, is distributed on 2 resonant frequencies :

$$F_{Bragg+/-} = -2\ Uo.v/\lambda \quad +/- \quad 0.1\ (F_{HHz})^{1/2}$$

with :

- Uo : radar steering vector ,
- v : current velocity,
- F_{MHz} : $c/\lambda = \omega/2\pi$ (λ = wave length)

The first order reflectivity is equal to :

$$\sigma^{(1)}(\omega) = \alpha\left\{\delta(\omega + 2k_0.v - \sqrt{g|2k_0|}).r(\theta) + \delta(\omega + 2k_0.v + \sqrt{g|2k_0|}).r(\theta+\pi)\right\}$$

where the magnitude coefficient α depends on the sea state and the frequency. For a given carrier frequency (for example 15 MHz), this coefficient reaches an asymptotic level of *-23dBm²/m²* when the wind velocity exceeds a certain threshold (for example 3 m/s @ 15 MHz).

Calculation of second order of Bragg lines is based on a dual series of wave numbers [k,k1] presenting a resonant combination according to the radar wavelength. A simplified computation technique [1] derived from Barrick theory can be used :

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **14 APR 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Use of STAP techniques to enhance the detection of slow targets in shipborne HFSWR**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Office National dEtudes et Recherches Aérospatiales (ONERA) Chemin de la Hunière et des Joncherettes, F-91761 Palaiseau**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001798, Proceedings of the International Conference on Radar (RADAR 2003) Held in Adelaide, Australia on 3-5 September 2003., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

$$\sigma^{(2)}(\omega)=|C|^2 4(2\pi)^5 k^4 \int d^2k \sum_{m=\pm1}\sum_{p=\pm1} S(mk)S(pk1)\ |\Gamma(k,k_1)|^2$$

$$.\delta(\Delta\omega+2k_0.V-m\sqrt{g|k|}-p\sqrt{g|k_1|})$$

with

$$\Gamma(k,k_1)=\frac{\{(k_0.k).(k_0.k_1)-2(k\ .k_1)\}}{\sqrt{|k\ .k_1|}} \qquad \textit{and} \qquad |C|^2=1/(2\pi)^4$$

where *S(.)* represents the sea wave gravity spectrum. Second order of Bragg line also depends on frequency and sea state. In the upper HF band (15-30 MHz) the level of the second order is much more sensitive to sea state than in lower band (below 10 MHz), where sea surface can be considered as "smooth according to the wavelength". Level of second order can be from -60 to -34 dBm^2/m^2 (for a coherent integration time of 100 s) depending on the wavelength and the seastate [2].

Then, in a motionless configuration the Bragg spectrum presents the shape shown on figure 1. Spectrum has been computed for a coherent integration time of 90 seconds, at 15 MHz, for a wind of 8m/s. The Pierson Moscovitz gravity spectrum was considered. Targets of interest (ships) are endo-clutter with a Doppler between -1Hz and 1Hz (radial velocity lower than 10m/s @ 15 MHz).

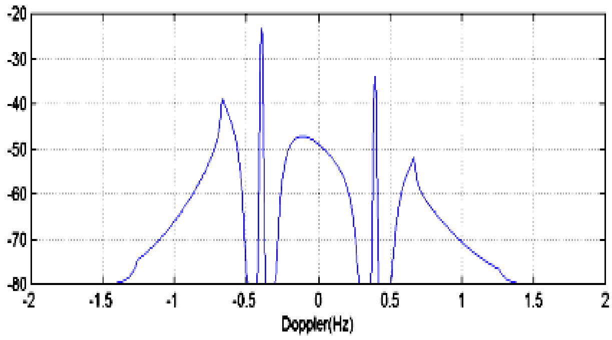


Fig. 1. : Bragg spectrum, 15 MHz, wind 8 m/s;
no current; wind vector parallel to radar axis

In a motionless configuration (for example coastal radar), ship echoes are detected through Doppler processing and two cases are possible:

- If the target Doppler shift coincides with one of the Bragg lines, carrier frequency has to be changed to provide another chance to detect the target. Else, waiting for Doppler changing (i.e. several minutes for ships) allows to detect the target.
- If the target detection is disturbed by the second order of Bragg clutter, detection enhancement can be obtained from improving the range resolution, as far as a wider frequency bandwidth can be available for radar detection purpose.

Figure 2 shows an experimental result obtained from a coastal HFSWR system at 16 MHz. Target is a commercial ship (oil tanker class).

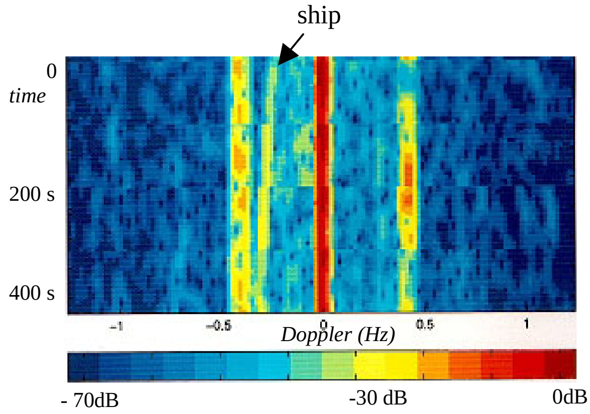


Fig. 2 . Example of HFSWR detection at 16 MHz , coastal radar

III. CLUTTER IN SHIPBORNE HFSWR

Motion consists of translation, pitch and roll, as shown on figure 3. We consider the following set of parameters (for a sea state 5) relative to a large ship (frigate class) equipped with a dynamic stabilisation system (transfer of ballast):

- Roll : magnitude +/- 6.5°, period 12 seconds
- pitch : magnitude +/-10°, period 6 seconds
- velocity (V) : 10m/s

Due to linear motion, sea echoes in each azimuth θ suffer from an additional Doppler shift equal to:

$$\Delta f=2V/\lambda\ .\sin(\theta)$$

Thus, clutter is distributed along an oblique ridge in the plane [Δf , sin(θ)].

Effect of pitch and roll has to be computed. A dual rotation matrix is considered and the additional phase distortion calculated between each antenna and any current position M (figure 3).

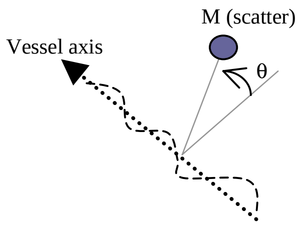


Fig. 3 .

The map of figure 4 gives the Doppler response of any point M (of polar coordinates [θ ,r]) in a wide angular sector from -90° to 90° with reference to the normal axis of the ship. Only phase distortion has been considered. Pitch and roll create additional parallel clutter ridge of lower magnitude The configuration is equivalent to have a translation motion with a modulated velocity. Effect is more significant for high value of squint angle θ.

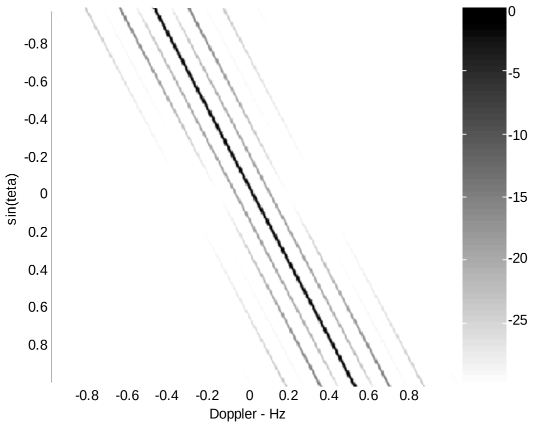


Fig. 4. Azimuth - Doppler response

From the Bragg spectrum and the Doppler response studied previously it is now possible to compute the effect of motion on a global landscape of sea surface scatters. Assuming no correlation between the statistics of signals coming from different directions we can write:

$$S(f) = \int D(\theta).R_{dop}(\theta, f).S_{Bragg}(f).d\theta$$

where $D(\theta)$ is the directional pattern, $S_{bragg}(f)$ is the Bragg spectrum(1st and 2nd orders) and $R_{dop}(\theta,f)$ the Doppler response computed above.

Figure 5 gives the result at 15 MHz and 25 MHz, for a sea state equal to 5. Several curves are superimposed in order to understand the contribution of each component of the motion to the global distortion. Thus, with reference to the onshore configuration, translation creates a spread of the 1st order Bragg line. Pitch and roll without translation create spurious at a level below the 2nd order. When the ship is moving, pitch & roll effect does not modify significantly the shape of the clutter curves (see the black and red dotted lines).

All these curves of course take into account a weighting window (Hanning) to reduces the Doppler processing secondary lobes and avoid a wrong interpretation of clutter spurious.

This first analysis shows that in our case (small pitch & roll deviations) the main effect is due to translation. Then, priority will be given to algorithms such as STAP, matched to linear motion and able to restore the detection of slow targets originally embedded in the spread sea clutter.

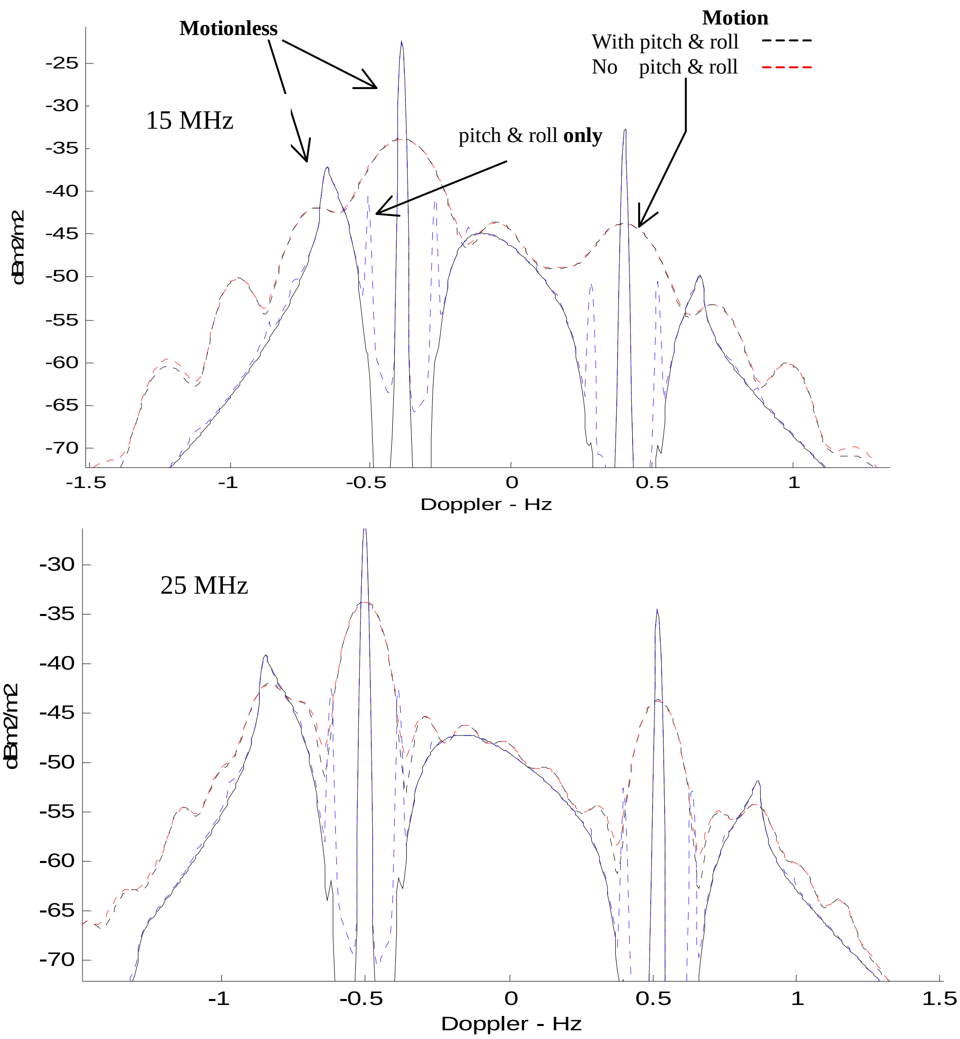


Fig. 5 . Simulation of motion effect on Bragg spectrum, including pitch and roll

IV. USE OF STAP TECHNIQUES

A. Introduction

STAP consists of adaptive techniques which allow to reduce the influence of clutter spread spectrum. These techniques are used in airborne domain to enhance the detection of small target , also to achieve the detection of ground target (GMTI). Compared to airborne domain, HFSWR present several differences :

- frequency band and waveform (PRF, duty cycle, unambiguous in range and velocity)
- clutter phenomenology (Bragg scattering)
- velocity of the platform,

In a conventional STAP approach, a space time weighting vector W is searched as a solution of a minimisation problem :

$L(W,\lambda) = W^H RW + \lambda .(T^H W-1)$, where W,λ are unknown and R is the space time covariance matrix The well known solution presents the following form :

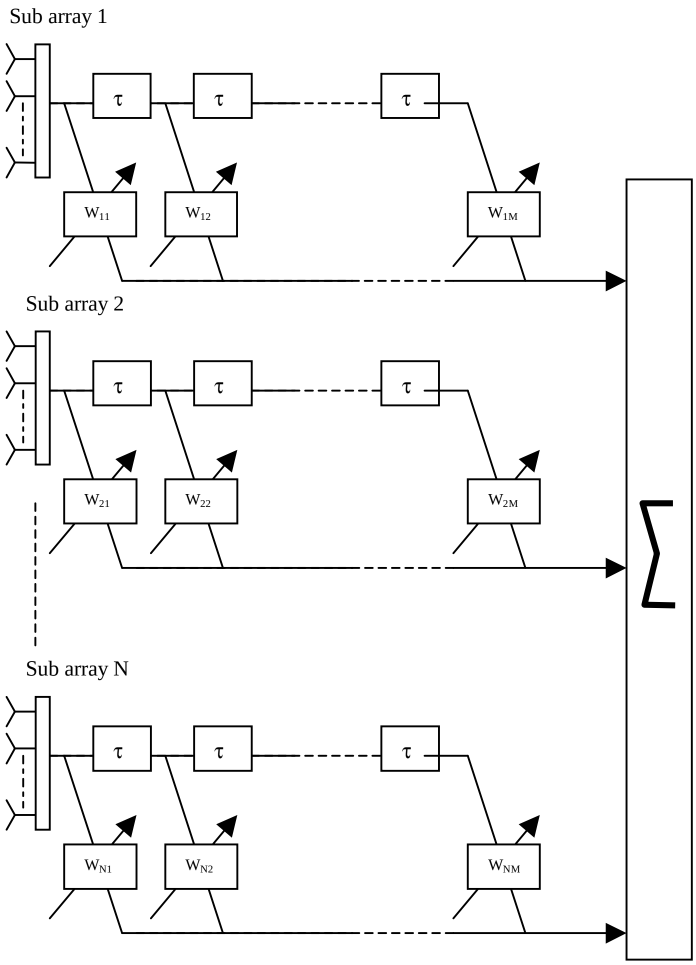
$$W_{opt} = R^{-1}T\left(T^H R^{-1}T\right)^{-1} \qquad Y = \frac{T^H R^{-1}X}{T^H R^{-1}T}$$

where X is the data vector, T is steering vector of the target (for a linear array, the phase is equal to $2\pi/\lambda\ [i_a \sin(\theta_{target})a + i_r V_{target} Tr]$, where a is the array step and Tr the repetition period, $[i_a,i_r]$ being the index of antennas and recurrences)

We can notice that $R^{-1}X$ operates a filtering of input signals with respect of the clutter covariance matrix. Digital beamforming and Doppler processing are derived from multiplication by T^H. In fact, this last operation can also be done more easily through a 2D-FFT and the normalisation term $TR^{-1}T$ can be omitted in a simplified approach, if a CFAR detection is applied after STAP filtering.

Figure 6 shows the conventional architecture of a STAP processor. The receiving antennas are gathered in subarrays (in our case for example, 16 antennas in 4 subarrays of 4 elements).

The sub array architecture is required to reduce the complexity and achieve the accurate estimation of the covariance matrix R. Feasibility of this estimation will be discussed in a further section. Data from each sub array are delivered at different times, following uniform taps τ, 2τ, ..$M\tau$. The delay τ represents a multiple of the recurrence period, for example 500 ms in the case of HFSWR. This delay is corresponding to a first coherent Doppler integration of 500 pulses, assuming a classical PRF of 1KHz (figure 7).



τ = 500 ms, M=9, N= 4 or 8

Fig. 6 . STAP conventional architecture

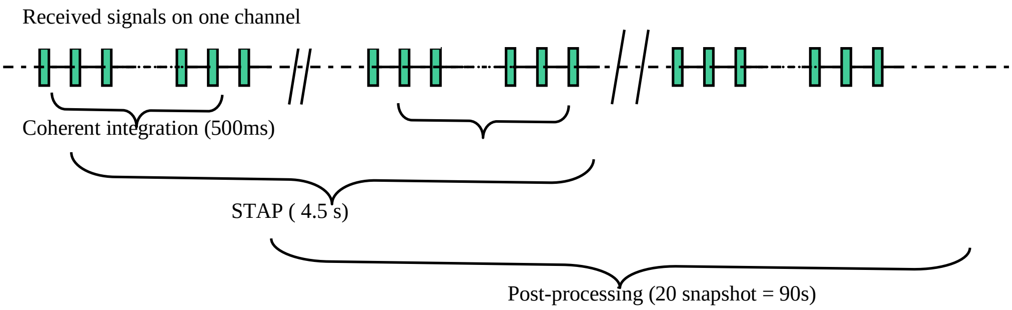


Fig. 7 . Time sequences for STAP processing

B. STAP Simulation

Simulation of STAP has been done in the following conditions :

- carrier frequency : 15 MHz
- radar signals are considered in a Doppler interval of –1 Hz à +1 Hz following a first coherent integration of 500 ms duration(figure 7).
- Bragg lines are considered with the following arbitrary magnitude : 65% for negative line, 25% for the positive line, and 10% for the centre line (zero Doppler); for each line, a random gaussian process has been generated to represent the sea scatters statistic. Not any correlation is assumed to exist between the negative and positive line. These two assumptions (gaussian and no correlation) should be verified through experimental investigations.
- 4 or 8 antennas channels have been considered from a receive passive antenna installed on the broadside of the ship. The antenna is 120 meters length .
- 9 taps (of 500ms)are considered.
- size of the covariance matrix is [72 x 72] or [36 x 36] depending on the number of sub arrays.

STAP filter is applied to signals along a duration of 9 x 500 ms = 4.5 sec.
A post processing of 20 STAP results is made, so that the total processing time is equal to 90 seconds. The ship velocity is equal to 10 m/s.

Simulation results are shown on figure 8. Target presents a Doppler shift of 0.2 Hz and an azimuth angle of -17°. Target amplitude has been adjusted to present - in a exo-clutter assumption - a signal to thermal noise ratio of 13 dB.

As the filter is not normalised by $T^H R^{-1} T$, we can see in the region of clutter the presence of residual echoes (false alarms). However the side lobes of the main clutter region has been reduced making possible the detection of the target.

Post-processing has been considered in this simulation as non coherent. Coherent processing is possible but requires to compensate the pitch and roll from one snapshot of to the following (every 4.5s). This compensation can be done using the pitch & roll measurements provided by a position and orientation system. Commercial on the shelves equipment provide angular accuracy better than 1° and can be used successfully. A coherent integration (compared to a non coherent one) allows to improve the signal to noise ratio of 3dB and to get a better Doppler discrimination.

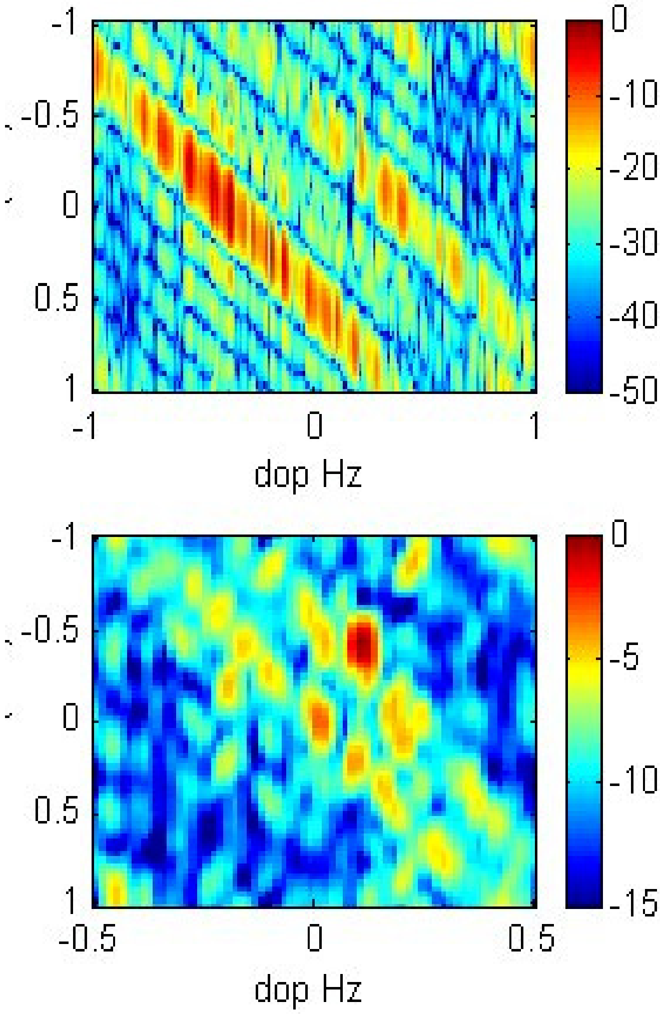


Fig. 8. Simulation of STAP technique

C. Estimation of Covariance matrix

In the simulation shown above, covariance matrix has been estimated around the target cell, without any constraint on availability of range samples. Estimation of covariance matrix is subjected to gather enough samples in range to make this estimation accurate. Usually, estimation of a covariance matrix of size [NM,NM], 2NM samples are needed to approach the optimal performances (-3dB loss), where N is the number of taps and M the number of space channels. Assuming 9 taps (delays) and 4 space channels, 72 range cells are needed. Considering a range resolution of a few kilometres to ten kilometres (a common value for HF radar), the range interval required for estimation should be very large, up to 200 or 300 km. In this interval, variation of sea current and sea state can make risky and inaccurate the covariance estimation. Then, the solution consists of using an wider band (thinner range resolution) waveform dedicated to covariance estimation and a conventional waveform for radar detection. These two waveforms are interleaved as shown on figure 9. Repetition period is doubled. The wide band waveform is a sparse pulse waveform where the pulse duration is the same as for the original waveform ; frequency is changing from pulse to pulse according to a set of frequencies previously selected with respect of occupied channels. Covariance matrix can be estimated in frequency domain more easily than in time domain. Assuming a range interval of 15 km for covariance estimation, pulse duration is equal to 100µs. For a PRF of 500Hz, up to 250 frequencies can be selected. For a covariance matrix size of [36,36], 72 channels are needed for the estimation. Assuming that 50% of the channels are not clear, the total required bandwidth (B_{cov}, for covariance estimation) is equal to 720 kHz around the centre radar frequency. For a radar frequency of 15 MHz, estimation has to be performed between 14.64 MHz and 15.36 MHz. Within this bandwidth, dispersion due to variation of Bragg lines (from 0.38262 Hz to 0.39192 Hz ~ 9 mHz) is negligible for a STAP applied on a duration of 4.5 seconds. Antenna calibration needs also to be considered in this wide bandwidth; as for Bragg lines, strong dispersion of antenna response is theoretically unexpected if the length of the array (~100 m) is smaller than c/ B_{cov}, and small variations can be compensated through calibration.

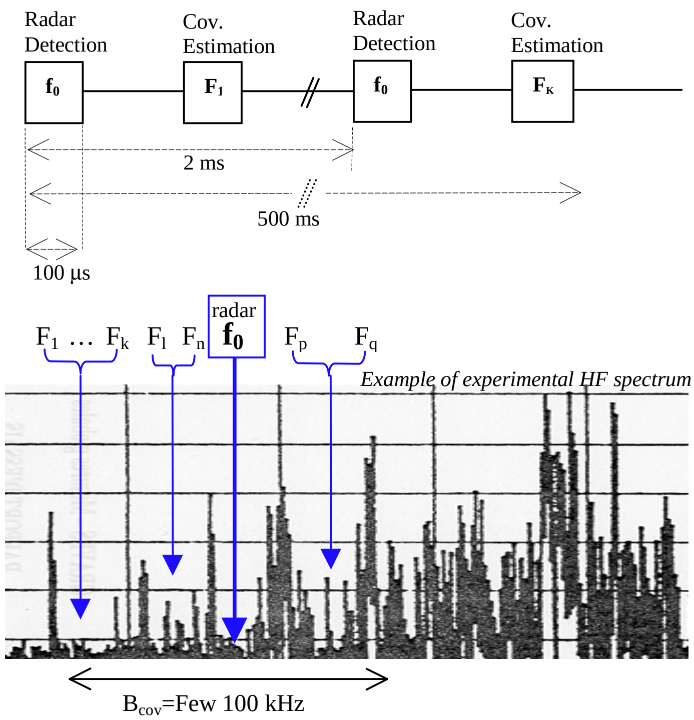


Fig. 9. HFSWR waveform matched to STAP

Due to the high reflectivity of clutter (compared to level of desired targets), the average power per frequency channel, for the 'learning' waveform can be very low, thus compensating the inconvenient of such a wide band transmission in the HF band.

Other solutions, to decrease the complexity of STAP implementation are on study. In particular, emergence of sub-optimal techniques presents a great interest [3].

CONCLUSION

This paper addressed the effect of motion on HFSWR and proposed the use of STAP techniques to improve the detection of slow targets.

Effect of linear motion, which produces a spread of Doppler echoes, can be compensated by use of STAP techniques in the same way as in airborne radar domain for GMTI purpose. STAP is also robust to small magnitude of pitch and roll, as considered in this paper. However, the case of higher angular deviation could be problematic in so far as linear techniques (like covariance filtering) cannot compensate rotation effects.

STAP has been discussed and illustrated from simulation results, assuming a gaussian clutter distribution and no correlation between the Bragg lines. Next steps of work must address experimentation with collection of real data in order to refine the properties of the sea clutter (in particular to address the correlation aspect of Bragg lines) and assess the performances of STAP algorithms.

Feasibility of STAP implementation has been discussed, taking into account the specificity of HFSWR waveform. To counter the rarefaction of range cells (due to the narrow band available on this kind of radar) we proposed to estimate the covariance matrix in frequency domain, from a set of sparse frequency available in the neighbourhood of the radar carrier frequency. This technique might be also verified and validated from real data in a next experimental step.

ACKNOWLEDGEMENT

This work has been realised with the financial support of DGA/SPN (Naval Program Service) in co-operation with THALES Air Defence.

REFERENCES

[1] R.E. ROBSON : Simplified theory of first and second order scattering of HF radio waves from the sea – Radio Science, Volume 19, Number 6, Nov-Dec 1984.
[2] E. D. RAMSEY SHEARMAN : A review of methods of remote sensing of sea surface conditions by HF radar and design considerations for narrow beam systems - IEEE Journal of oceanic engineering, Vol. OE-11, n°2, April 1986.
[3] R. KLEMM : Space-time Adaptive Processing, *IEE, London, UK,* 1998.
[4] J. XIE, Y. YUAN and Y. LIU : Suppression of sea clutter with orthogonal weighting for target detection in shipborne HFSWR - IEE Proceedings, Radar sonar and navigation, Vol. 149, N°1, February 2002.